The Impact of Local Pollution Exposure on Hospital Admissions: The Case of Portugal

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Abstract

The World Health Organization has reviewed downwards the air quality guidelines, having more severely tightened the annual recommended nitrogen dioxide (NO2) standard. Yet, economic research focused on assessing the impact of this criterion pollutant on health outcomes is still lacking. This paper aims to fill this gap by estimating the impact of the daily concentration of nitrogen dioxide (NO2) on the number of hospital admissions due to respiratory-related reasons in Portugal between January 1, 2016, and December 31, 2018. I find that a 1 microg/m3 increase in daily nitrogen dioxide (NO2) concentration increases the number of hospital admissions due to specific respiratory-related reasons (pneumonia, COPD, asthma) by 2.6% among children 2 to 5 years old. For this cohort, back-of-the-envelope costs estimates amount to 830 thousand euros (2018), representing 0.1% of the total annual health budget of the country. I also show that in Portugal, the richer, younger, and more educated population is concentrated in urban areas and relies on a car as the main transportation mode, being exposed to higher-than-average daily NO2 concentrations. Therefore, this study provides relevant data to better inform regulators to implement sustainable solutions, such as Low Emission Zones, to decrease ambient nitrogen dioxide levels in Portugal, improving the welfare of local populations.

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1. Introduction

The World Health Organization (WHO) and the European Environment Agency (EEA) consider air pollution one of the greatest environmental risks to health (EEA, 2020). The combined effects of ambient and household air pollution are estimated to have caused 6.7 million premature deaths annually (WHO, 2022). The WHO air quality standards were revised in September 2021, sixteen years after the previous standards were issued. All the criteria pollutants[2], except for sulfur dioxide (SO2), had their annual and 24-hour standards tightened[3]. The annual and 24-hour standards for particulate matter (PM10 and PM2.5) were reduced by 10% to 50%. However, the largest decrease (75%) targeted the annual value of nitrogen dioxide (NO2); its annual mean decreased from 40 to 10 microg/m3. Moreover, a new 24-hour standard of 25 microg/m3 was introduced (WHO, 2021).

Despite the severity of the new WHO guidelines and the tighter local and global air pollution policies that are expected to follow, economic studies that estimate the impact of nitrogen dioxide (NO2) on the health condition of local populations are lacking. Yet, to design sustainable abatement policies targeting that local pollutant, it is key to assess the net benefits that result from intervening to control for it. The present study aims to start filling this gap by estimating the impact of the daily concentration of nitrogen dioxide (NO2) on the number of hospital admissions due to respiratory-related reasons in Portugal between January 1, 2016, and December 31, 2018.

I find that a 1 $\mu g/m^3$ increase in daily nitrogen dioxide (NO2) concentration increases by 2.6% the number of hospital admissions due to specific respiratory-related reasons (pneumonia, chronic obstructive pulmonary disease (COPD), asthma) among the 2 – 5 years old children. When considering the group of the most polluted parishes in the country, the magnitude of the impact increases to 3.3%. The Lisbon Metropolitan Area (LMA), the capital Metropolitan area, is the country's most populated area and is part of the most polluted areas in the country. In this region, the estimated impact of a 1 microg/m3 increase in a daily concentration of nitrogen dioxide (NO2) on the number of hospital admissions due to specific respiratory-related reasons among 2 – 5 years old children increases to 17.7%. A back-of-the-envelope estimate of the costs of a 1 $\mu g/m^3$ increase in daily nitrogen dioxide (NO2) concentration is between 260 and 830 thousand euros (2018), representing 0.1% of the annual budget for the whole national

[2] Six ambient air pollutants are considered criteria pollutants and are monitored worldwide: nitrogen dioxide (NO2), particulate matter (PM10 and PM2.5), sulfur dioxide (SO2), lead, carbon monoxide (CO), and ground-level ozone (O3).

[3] The maximum 24-hour concentration of SO2 was increased from 20 to 40 microg/m3.

health system in 2018. I also show that in Portugal, the richer, younger, and more educated population is exposed to higher-than-average daily nitrogen dioxide concentrations, suggesting no sorting based on pollution levels. This can be explained by the fact that younger and more educated people tend to live in the cities, where more job opportunities and higher education institutions are concentrated. Moreover, 60% of the whole fleet of vehicles circulating in the LMA are private cars. As nitrogen dioxide (NO2) is one of the main urban traffic pollutants, the exposure in this urban area is very significant.

I divided all the parishes into four groups to identify possible non-linearities of the impact of nitrogen dioxide (NO2) concentrations on hospital admissions. Group four comprises parishes with the highest average daily nitrogen dioxide (NO2) concentration, while group one contains parishes with the lowest average daily nitrogen dioxide (NO2) concentration. The parishes in the LMA that belong to group four are mainly located in the historical city center (downtown), where one of the most important avenues in Lisbon, Avenida da Liberdade, is located. This area has narrow streets, high congestion levels during peak hours, and, at the same time, is the area where many offices are located. Therefore, considering the geographical location and the traffic dynamics of the most polluted areas in Lisbon, Low Emission Zones could be considered as a possible policy intervention to decrease ambient levels of nitrogen dioxide (NO2), as is the case in other European cities.[4]

Nitrogen dioxide (NO2) is a gaseous air pollutant composed of nitrogen and oxygen, and it belongs to a group of related gases called nitrogen oxides (NOx)[5]. It is formed when diesel and fossil fuels are burned at high temperatures. In urban areas, the primary sources of nitrogen dioxide are trucks, buses, and cars. Nitrogen dioxide (NO2) serves as a precursor for particulate matter (PM10 and PM2.5) and ozone (O3), and, when interacting with water, contributes to acid rain formation, negatively impacting sensitive ecosystems, such as lakes and forests (EPA, 2023).

Anenberg et al. (2022) show that average nitrogen dioxide (NO2) concentrations dropped by approximately 50% in the USA from the 1980s to the 2010s, presenting a slower decrease in Europe. Despite the observed decrease, global epidemiological studies show a significant negative impact of nitrogen dioxide (NO2) on hospital admissions due to pediatric asthma. In fact, Anenberg et al. (2022) showed that 1.85 million new pediatric asthma cases were

[4] The choice of the most appropriate policy intervention will require an assessment of the net benefits involved in each case, also weighting for the associated distributional effects. This is beyond the scope of this paper.

[5] American Lung Association. Nitrogen Dioxide. (https://www.lung.org/clean-air/outdoors/what-makes-air-unhealthy/nitrogen-dioxide)

attributable to nitrogen dioxide (NO2) globally in 2019. Achakulwisut et al. (2019) also showed that the largest burdens of new asthma cases associated with nitrogen dioxide (NO2) exposure were found in Andean Latin America, high-income North America, and high-income Asia Pacific, respectively. Ewald et al. (2021) claim that the 25% reduction in nitrogen dioxide (NO2) exposure may lead to 2.5 to 12 thousand fewer children experiencing asthma in New South Wales, Australia.

However, the exact biological mechanism of how nitrogen dioxide (NO2) affects a respiratory system has yet to be identified. Oxidative stress injury of free radicals (Kelly et al., 1996) and systematic inflammation (Xu et al., 2022) are proposed as possible explanations. Additionally, epidemiological literature has shown a significant negative impact of nitrogen dioxide (NO2) on hospital admissions due to hypertension (Ge et al., 2023), ischemic stroke (Li et al., 2022), Type 2 diabetes (Du et al., 2022), breast cancer (Amadou et al., 2023), and chronic obstructive pulmonary disease (COPD) among the elderly (Huang et al., 2021).

Despite the relevance of those figures, studies that focus on assessing the impact of nitrogen dioxide (NO2) on the health condition of local populations, in particular, on how it affects hospital admissions for the different age cohorts across space, worker productivity, or, more generally, on economic activity are still lagging behind. Only a few studies can be found. Lavy et al. (2022) and Vega-Calderón et al. (2021) estimate the impact of nitrogen dioxide (NO2) on work-related accidents in Israel and Spain, respectively. Filippini et al. (2019) show a significant impact of nitrogen dioxide (NO2) on hospital admissions due to cardiovascular-related reasons in Switzerland. The economic studies available have shown significant negative effects of particulate matter, specifically PM2.5, on health (Deryugina et al., 2019) and labor outcomes (Chang et al., 2016), cognitive abilities, test scores (Ebenstein et al., 2016), dementia (Bishop et al., 2023), suicide (Persico and Marcotte, 2022), and crime rates (Bondy et al., 2020). The other pollutants have not been studied so thoroughly.

This research aims to contribute to filling this gap, focusing on the case of Portugal. Even though the concentrations of nitrogen dioxide (NO2) have been decreasing in Europe, in June 2023, the European Union Court of Justice declared Portugal to be non-compliant with the European rules on air quality as the nitrogen dioxide (NO2) concentration was exceeding its limit in three areas of the country: the northern part of Lisbon, the western part of Porto and the area between the Douro and Minho river basins, north of the city of Porto[6]. Moreover,

[6] Renascença. June 29, 2023. "Tribunal de Justiça de UE: Portugal não cumpre regras de qualidade do ar”. (https://rr.sapo.pt/noticia/pais/2023/06/29/tribunal-de-justica-da-ue-portugal-nao-cumpre-regras-de-qualidade-do-ar/337251/)

according to the reviewed, more stringent WHO standards, Portugal is exceeding the daily and yearly limits set for nitrogen dioxide (NO_2). As local pollutants studies are still lacking in Portugal, this research is the first attempt to contribute to a better understanding of the consequences of nitrogen dioxide (NO_2) on the health condition of the Portuguese population for the period considered across space.

While Portugal has invested significantly in renewables[7] and has already decommissioned the coal power plants in 2021, the decarbonization of the transportation sector, responsible for the largest part of the nitrogen dioxide emissions (NO_2), is still in its infancy. The private car fleet plays an important role in this process because the existing public transportation network is very inefficient. Yet, this fleet is about 13.5 years old on average, with 25% of cars being older than 20 years old[8], and only less than 3% of private cars are electric cars, also reflecting the large inequalities among the Portuguese population and the lack of cost-effective and equitable public policies providing the appropriate incentives to overcome those gaps. In the context of the transition to carbon neutrality and given the country´s commitment to the EU goals, this is a very important issue to which I aim to contribute.

Nitrogen dioxide (NO_2) daily concentrations at a parish level vary in Portugal from just above 0 microg/m3 to more than 3 000 microg/m3, which allows for considering non-linear effects. Moreover, there are no country-specific enforced government urban policies related to air pollution in Portugal; therefore, as mentioned above, this study aims to provide a scientific base to better inform the design of more sustainable public policies, monitoring, and enforcement.

Air pollution monitoring is the primary data source to assess the concentrations of criteria pollutants worldwide. The network is rather scarce in Portugal, with 100 monitors for 2 874 parishes in continental Portugal. Yet, satellite imagery data can fill this gap. Therefore, having access to it is key for places where the monitoring network is almost nonexistent in general terms.

The typical concern when using satellite data for policy purposes is that the concentration levels measured by satellites do not reflect the concentrations in the surface level data[9] and,

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[7] Currently, Portugal can produce 17 gigawatts of energy from renewable sources. Since the beginning of 2022, additional 4 gigawatts have been approved. The government's objective is to have 80% of energy in the country to be produced from renewable energy sources. (https://www.portugal.gov.pt/pt/gc23/comunicacao/noticia?i=intencoes-de-investimento-em-energias-renovaveis-em-portugal-ascendem-a-60-mil-milhoes-de-euros)

[8] Eco Sapo. “Um em cada quantro carros em Portugal tem mais de 20 anos.” May 30, 2022. (https://eco.sapo.pt/2022/05/30/um-em-cada-quatro-carros-em-portugal-tem-mais-de-20-anos/)

[9] Surface-level data is 2 meters above the ground.

therefore, cannot be used as the basis for policy recommendations. While this is the case for secondary pollutants, such as PM2.5 and PM10, due to the complexity of the chemical interactions between the pollutants, for nitrogen dioxide (NO2) the situation is different given its characteristics. Nitrogen dioxide (NO2) is a primary pollutant directly emitted into the atmosphere and is short-lived. These two factors allow satellites to capture the concentration of nitrogen dioxide (NO2) emitted shortly before, allowing for a reliable, measurable basis that can be used for policy purposes. Satellite data may still not reflect the exact concentrations measured by the monitoring network, but can capture the differences in exposure, allowing for estimating the impact of the pollutant concentration. For example, on August 8, 2016, a 5-day period of wildfires started in Madeira Island and in the northern part of continental Portugal. The satellite data registered a sharp increase in the nitrogen dioxide (NO2) concentration on those days and a decrease to its normal levels after the wildfires (Figure 1). Moreover, Figure 1 shows that other pollutants, like particulate matter (PM10 and PM2.5) and ozone (O3), take longer than nitrogen dioxide (NO2) to decrease to the initial levels. This suggests that the satellite imagery data can capture variations in concentration levels and that nitrogen dioxide (NO2) has an acute impact on the considered outcome.

Currently, several reanalysis datasets for the pollutants are available. Reanalysis datasets use satellite data on pollutants' concentrations, chemical atmospheric transport models, weather variables, and concentrations obtained from other sources to calculate the surface concentrations of nitrogen dioxide and other pollutants.[10]. Geddes et al. (2016) hypothesize that as satellite data assess the area-averaged record, they represent what a randomly distributed monitoring network would obtain, potentially mitigating systematic biases in exposure studies. Examples of studies that used satellite-derived pollutants' concentrations include the estimation of surface-level NO2 concentrations in Finland (Virta et al., 2023), the research in Italy focusing on the association between air pollution and COVID-19 mortality rates (Filippini

[10] The CAMS reanalysis dataset includes three-hour data on all criteria pollutants except lead with the resolution 0.75 by 0.75 degrees from January 1, 2013, till December 31, 2022. (https://ads.atmosphere.copernicus.eu/cdsapp#!/dataset/cams-global-reanalysis-eac4?tab=form). The Aura Validation Data Center (AVDC) has monthly and daily nitrogen dioxide concentrations with 0.1 by 0.1 degrees resolution between January 1, 2005, and December 31, 2020. (https://avdc.gsfc.nasa.gov/pub/data/satellite/Aura/OMI/V03/L4/OMI_Surface_NO2/) The Washington University in St. Louis Atmospheric Composition Analysis Group provides annual and monthly data on PM2.5 surface concentrations at 0.1 by 0.1 and 0.01 by 0.01 degrees between 1998 and 2021. (https://sites.wustl.edu/acag/datasets/surface-pm2-5/). They also provide the annual ground-level estimates of nitrogen dioxide concentration at ~ 1 km resolution between 2005 and 2019. (https://sites.wustl.edu/acag/datasets/surface-no2/)

et al., 2021), and the derivation of the nitrogen dioxide (NO_2) concentration at city level worldwide (Cooper et al., 2022).

This paper contributes to the current literature in several ways. First, I estimate the impact of daily nitrogen dioxide (NO_2) concentrations on health outcomes. Importantly, while this pollutant has received little attention in the economic literature, recently, its standards have been severely tightened. Second, I present the results based on satellite-based reanalysis tools to leverage specific characteristics of nitrogen dioxide (NO_2) to showcase the use of satellite data in the impact of air pollution research. Third, I focus on Portuguese data as Portugal is an example of a developed country with elevated levels of nitrogen dioxide (NO_2) in some areas, as explained above, which allows for investigating about potential non-linearities and, therefore, possible thresholds in the exposure to nitrogen dioxide (NO_2). Moreover, as Portugal has not presented any air pollution mitigation plan in response to the claim of the European Court of Justice, this research may facilitate the adoption of well-grounded, data-based policies that will, hopefully, contribute to improving the air quality in the country and the welfare of local populations.

The rest of the paper is organized as follows. Section 2 describes the data sources. Section 3 details the empirical methodology. Section 4 presents the results, and Section 5 concludes. Tables and figures are included in the Appendix.

2. Background and Data

In this study, I use daily datasets of (i) parish-level concentrations of criteria pollutants obtained from the Aurora Validation Data Centre (AVDC) and the Copernicus Atmosphere Monitoring Service (CAMS) satellite data reanalysis tools and (ii) individual-level hospital admissions. The socio-economic characteristics at a parish level were obtained from the National Statistics Institute Census 2021 dataset. The period under analysis is between January 1, 2016, and December 31, 2018. A patient's address is available up to the parish level; therefore, both pollutant concentrations and the number of hospital admissions are calculated at the parish-day level.

2.1 Portugal administrative division

According to Census 2021, 10 343 066 individuals live in Portugal. The country is divided into 18 districts[11], 308 municipalities[12], and 3 091 parishes[13]. It consists of continental Portugal, the Autonomous Region of the Azores, and the Autonomous Region of Madeira. Table 1 presents summary statistics of various characteristics of the country at a parish level. Each parish has between 19 and 68 649 inhabitants. On average, there are 8 189 citizens in each parish. The average monthly income per individual is 943.1 euros (2018)[14], but depending on the municipality, it varies between 4 243 and 13 043 euros (2018). The average age is 50 years old. In each parish, most people are between 30 and 80 years old. There are more females than males (52% vs. 48%). On average, a person spends 18.6 minutes commuting, and most of the parishes' citizens live and work in the same municipality but in different parishes. This commuting time corresponds to approximately 15 km trip by car.

In this study, all the datasets are constructed for continental Portugal, which has 18 districts, 278 municipalities, and 2 882 parishes (Figure 2).

2.2 Pollutant concentrations data

The Portuguese Environmental Agency (Agência Portuguesa de Ambiente (APA))[15] manages the pollutants' concentrations monitoring network that measures criteria pollutants' concentrations[16] hourly since 2001. Currently, the data is available between 2001 and 2021[17].

There are 100 monitoring stations in Portugal, but only 67 stations were active during the period considered. They are mainly located in the coastal area of Portugal (Figure 3). Table 2 presents the hourly, daily, and yearly summary statistics for each pollutant in Portugal between January 1, 2016, and December 31, 2018. Nitrogen dioxide (NO2) is the second pollutant with

[11] Aveiro, Beja, Braga, Bragança, Castelo Branco, Coimbra, Évora, Faro, Guarda, Leiria, Lisboa, Portalegre, Porto, Santarém, Setúbal, Viana do Castelo, Vila Real, and Viseu.

[12] 278 municipalities are in the continental part of Portugal, 11 are on the Madeira islands, and 19 are on the Azores islands.

[13] 2 882 parishes are in the continental part of Portugal, 54 are on the Madeira islands, and 155 are on the Azores islands.

[14] I use the data on the monthly income of those who are not self-employed. This figure is representative of the income in Portugal, as more than 90% of the working population is not self-employed. (https://www.pordata.pt/municipios/trabalhadores+por+conta+propria+total+e+por+nivel+de+escolaridade+completo-837)

[15] The QualAr platform. (https://qualar.apambiente.pt/)

[16] Ozone (O3), nitrogen dioxide (NO2), nitrogen oxide (NO), nitrogen oxides (NOx), carbon monoxide (CO), sulfur dioxide (SO2), particulate matter (PM10 and PM2.5), benzol (C6H6).

[17] Only some stations have been continuously active since 2001; some were introduced later or stopped working before 2021.

the highest hourly concentration obtained, 3 614 microg/m3[18]. The maximum daily concentration registered is 1 468 microg/m3. Even though Portugal, on average, does not experience nitrogen dioxide (NO2) concentrations above the WHO 1-hour limit of 200 microg/m3 or the annual limit of 40 microg/m3, peak values (18 and 19.5 times higher than the limits) indicate the variability in the concentrations inhaled by the Portuguese population in different country's regions also showing that there are regions with very high average inhaled concentration levels. However, it is important to note that according to the new WHO standards, Portugal would be in a non-attainment state for nitrogen dioxide (NO2) for daily and yearly limits[19].

In the literature, it is well-known that the monitors are strategically placed (Grainger and Schreiber, 2019); therefore, the extrapolation of their readings for larger areas may not describe the real inhaled concentrations in the area. For example, the monitoring station in the Avenida Liberdade in Lisbon is located in the downtown part of the city, in the parish of Santo António. It registers the highest nitrogen dioxide (NO2) concentrations in the city; the average hourly value is 542 microg/m3. Extrapolating this value for the whole parish would mean that the Santo António parish is one of the most polluted parishes regarding hourly inhaled nitrogen dioxide (NO2) concentrations. Still, the parish's landscape is very diverse, with valleys and hills, and except for the Avenida Liberdade, a highly polluted area identified as a "street canyon"[20], it has many green areas, such as in Rua Camilo Castelo Branco, Torel, and the Marcelino Mesquita gardens, where we can expect lower pollutant concentrations. Satellite data allows overcoming these differences and considering the average exposure to pollutants for a specific area[21].

[18] The first one is nitrogen oxides (NOx), but this is the general group that includes both nitrogen dioxide (NO2) and nitric oxide (NO); therefore, nitrogen dioxide (NO2) has the highest maximum value among the individual pollutants.
[19] The 2021 WHO air quality guidelines set the nitrogen dioxide (NO2) annual limit concentration at 10 microg/m3 and daily concentration at 25 microg/m3.
[20] A street canyon is created when a street is flanked by tall buildings on both sides, which results in a canyon-like appearance. Street canyons affect the movement, direction, and speed of the wind, affecting the air quality and temperature.
[21] As satellite data provide the average exposure to pollutants, the ideal setting would be having a highly developed monitoring network that could be combined with the granular individual-level hospital admissions data, but due to hospital admissions data restriction at the address level of patients (parish level) concentrations derived from satellite data reflect the average exposure better.

Satellite data on pollutants' concentrations were obtained using satellite-based reanalysis tools[22]: the Aura Validation Data Center (AVDC) dataset[23] (nitrogen dioxide (NO2)) and the CAMS reanalysis dataset[24] (particulate matter (PM10 and PM2.5), carbon monoxide (CO), sulfur dioxide (SO2), ozone (O3), nitrogen dioxide (NO2)). The AVDC provides daily concentrations of nitrogen dioxide (NO2) at the 0.1 by 0.1 degrees scale (~ 11 by 11 km) (Figure 4), and the CAMS reanalysis tool provides daily concentrations of other pollutants at the 0.75 by 0.75 degrees scale (~80 by 80 km) (Figure 5).

Table 3 presents the summary statistics for each pollutant obtained with the AVDC reanalysis tool (1 925 points cover Portugal, each point has 1 096 daily observations) and the CAMS reanalysis tool (91 points cover Portugal, each point has 1 096 daily observations). The average daily level of nitrogen dioxide (NO2) derived from the AVDC reanalysis tool is 1.4 microg/m3, 22 times less than the average daily level obtained from the monitors. Nitrogen dioxide (NO2) concentration obtained with the CAMS reanalysis tool is higher than with the AVDC. The CAMS reanalysis tool obtains the nitrogen dioxide (NO2) concentration from a larger area (1600 square km in comparison to the AVDC 121 square km), and, therefore, it can capture the average value of more heterogeneous concentrations. The AVDC reanalysis tool has a smaller scale, allowing for the concentrations to be calculated more precisely and above a more homogeneous landscape.

For every pollutant, except carbon monoxide (CO), the average values registered by the monitoring network are higher than those derived from the reanalysis tools. This may result from different measuring approaches: the reanalysis tools average the satellite data over a resolution area, and the monitor registers the pollutant concentration at a certain point at the surface. Moreover, the monitors are often placed strategically to control for the pollution levels due to human-related activity or traffic emissions, typically registering elevated levels.

Even though, on average, the reanalysis data on pollutant concentrations are lower than those registered by the ground-level monitors, they are representative of the impact of nitrogen dioxide (NO2) exposure. To show it, I identify the closest satellite data point to each monitoring station and calculate the correlation coefficient for each pollutant. The correlation coefficient

[22]The reanalysis tool uses data on pollutant concentrations registered by the satellite. It combines the obtained data with the weather variables information on pollutants' concentrations from other sources and exploits the chemical transportation model to derive the final value.

[23] The Aura Validation Data Center (AVDC) dataset produced by NASA covers the period between 2003 and 2021; the resolution is 0.1 by 0.1 degrees.

[24] The Copernicus Atmosphere Monitoring Service produces the CAMS reanalysis dataset, covering the period between 2003 and 2022; the resolution is 0.75 by 0.75 degrees. The CAMS is the latest global reanalysis dataset of atmospheric composition.

between the registrations of the monitors and the AVDC dataset points for nitrogen dioxide (NO_2) is 0.192, and the correlation coefficient between the registrations of the monitors and the CAMS dataset varies from -0.180 to 0.010, depending on the pollutant[25]. The more granular resolution of the reanalysis data contributes to a higher correlation between the registrations obtained from the monitors and those from satellite-based derived concentrations due to a higher precision level in the derivation of the satellite data reanalysis tool concentrations.

To obtain parish-level concentrations with satellite reanalysis tools data, I have created a square around each point of the dataset. Then, I calculate the percentage of each square that overlaps with the parish area. Using these percentages as weights, I calculate the weighted average daily concentration for each pollutant for each parish. Table 4 presents the summary statistics of the parish-level concentrations.

2.3. Hospital admission data

Hospital admissions data were provided by the Central Administration of the Health System of Portugal (Administração Central do Sistema de Saúde, ACSS). The dataset includes individual hospital admissions between January 1, 2016, and December 31, 2018. The home address of each patient is known up to a parish level. Each observation includes the unique fake identifier of a patient, ICD 10 code of admission, date and hour of admission, indication if it was an emergency admission, date of release from the hospital, and personal characteristics, such as age and gender. Table 5 presents the summary statistics for the hospital admissions dataset. Hospital admissions include inpatient and outpatient cases. Outpatient hospital admission means a person does not spend a night at the hospital. In contrast, inpatient hospital admission requires that a patient spends at least one night in the hospital.

Between January 1, 2016, and December 31, 2018, there were 4 438 473 individual hospital admissions, 2 045 809 individuals (886 311 were male, 1 159 498 were female). There were 2 191 720 cases of outpatient hospital admissions and 2 246 753 cases of inpatient hospital admissions. On average, patients spent 7.7 days in hospital (Table 5). Patients were between 0 and 110 years old. Most patients were between 51 and 80 years old, with the mean patient age being 57. However, there is a significant group of children between 0 and 1 years old, where 0 years old means less than one year old. Knowing the date of admission and the

[25]The correlation coefficient for $PM_{2.5}$ is 0.010, SO_2 is -0.180, PM_{10} is -0.036, CO is -0.0004, O_3 is -0.028, NO_2 is -0.061.

date of birth allowed me to calculate the age of children below one year old expressed in months. The database includes giving birth cases, but as the dataset is not purely dedicated to giving birth, we cannot use it to analyze the newborns.

Table 6 presents summary statistics for the general, outpatient, and inpatient hospital admissions for respiratory-related reasons. In the three years, there were 279 446 cases of hospital admissions due to respiratory-related reasons, 6.3% of all hospital admissions. 39 062 cases were outpatient (1.8% of all outpatient cases), and 240 384 cases were inpatient cases (10.7% of all inpatient cases). There were 223 410 individuals admitted due to respiratory-related reasons: 193 252 individuals had at least one inpatient hospital admission due to respiratory-related reasons, and 33 480 individuals had at least one outpatient hospital admission due to respiratory-related reasons. The average age of the patients admitted to the hospital due to respiratory-related reasons is 59 years old; for the outpatient cases, the average age is 43 years old, and for the inpatient, it is 61 years old. Average inpatient hospital admission cases last, on average, for nine days, which is higher than for inpatient hospital admission, regardless of the cause. All age groups, except for children between 0 and 1 years old and elderly above 71 years old, show higher percentages of all kinds of hospital admissions due to respiratory-related reasons in outpatient compared to inpatient cases. This means that the probability of a child between 0 and 1 years old or an elderly person above 71 years old being admitted to hospital due to respiratory-related reasons and spending at least one night in hospital is higher than for other age groups.

3. Methodology

When working with the satellite reanalysis data, I use a negative binomial model to estimate the impact of daily nitrogen dioxide (NO2) concentration on the number of hospital admissions at a parish level.

The estimated equation is the following:

$$Y_{tp} = \exp\left(\beta * NO2_{tp} + \gamma * W_{tp} + \rho_{tp}\right) \tag{1}$$

where Y_{tp} is the number of hospital admissions on day *t* in parish p, $NO2_{tp}$ is the concentration of nitrogen dioxide (NO2) on day *t* in parish p, W_{tp} is a matrix of other pollutants (particulate matter (PM10) and ozone), and their one- and two-days lagged values[26]. I control for the parish-level fixed effects and cluster standard errors at a parish level. I do not need to control for the weather characteristics at a parish level because the satellite data reanalysis tools already incorporate this information in their chemical transportation models.

Variability of the concentrations at a parish level in Portugal allows for exploring possible non-linear relationships between the daily nitrogen dioxide (NO2) concentrations and the number of hospital admissions due to respiratory-related reasons. To do this, I calculate the average daily nitrogen dioxide (NO2) concentration that individuals are exposed to in each parish during the period considered and divide the parishes into four groups. Group one contains all the parishes that inhale, on average, the lowest daily NO2 concentrations, and group four includes the parishes that inhale the highest NO2 concentrations (Figure 6). Parishes belonging to group four are mainly located in the Lisbon and Porto Metropolitan areas and around the Sines refinery plant. Table 7 summarizes the different characteristics of the parishes in each group. The average daily nitrogen dioxide (NO2) concentration increases from 0.7 microg/m3 for parishes in group one to 2.2 microg/m3 for parishes in group four. Parishes in group four have 6.8 times more residents than those in group one. On average, the residents of parishes in group four are younger, have higher education levels, and work in the same municipality but in a different parish, spending 19.6 daily commuting minutes. Therefore, Portugal's richer, younger, and more educated residents are exposed to higher pollution levels. This results from the concentration of jobs in cities, thus explaining the largest numbers of a younger and more educated population living there and the fact that nitrogen dioxide is mainly an urban traffic pollutant. These findings call for developing and implementing an efficient (or cost-effective) policy to decrease traffic air pollution concentrations in urban areas, not forgetting about equity concerns.

The Lisbon Metropolitan has 2 870 208 residents (Table 8). The average daily nitrogen dioxide (NO2) concentration is 2.1 microg/m3, which is 50% higher than the average concentration in the country. Lisbon Metropolitan Area is a diverse area in what concerns socio-economic characteristics. It includes parishes that have from 1 566 to 68 649 residents. The average monthly income per individual per parish is 1 168.2 euros (2018). This is 1.2 times higher than the average monthly income in the country. Though, in line with duality found in the country, it varies between 641 euros and 2 048.8 euros (2018). The average monthly rent

[26] Other pollutants include particulate matter (PM10) and ozone (O3). Also, I include one and two-day lagged concentrations of nitrogen dioxide (NO2), particulate matter (PM10), and ozone (O3). PM2.5 was not included in this regression as it has a high (0.97) correlation coefficient with particulate matter (PM10).

varies between 10 and 426.36 euros. The percentage of higher education completed at a parish level is between 8.5% and 61.1%. The average age of the Lisbon Metropolitan Area parish residents is 44 years old, which is lower than the average age in the country, varying between 39 and 53 years old. Due to the lack of affordable housing in the city, most people live and work in different municipalities within the Lisbon Metropolitan Area, which means a high level of commuting, as mentioned before. This fact and a very inefficient public transportation network explain the significant number of private cars entering the city daily and the elevated levels of NO2 in some specific routes and areas.

Due to the diversity of socio-economic characteristics in the Lisbon Metropolitan Area (LMA), I divided all the LMA parishes into four groups, as previously done for all the parishes in the country (Figure 7). Group one has the lowest average level of daily nitrogen dioxide (NO2) concentration, and group four has the highest average daily level. Table 9 presents summary statistics for each of the groups. The four groups are very similar with respect to average age, education level, commuting time, and patterns. The parishes in group four present the highest individual monthly income; the value is high in group one because of the Alcochete municipality; the average monthly income of its residents is the highest in the country, 2 048.8 euros (2018). Overall, the average individual income in each group is higher than the average in the country. Therefore, we still may conclude that the richer population in the Lisbon Metropolitan Area is exposed to higher levels of NO2 pollution. On average, more populated parishes also have the highest nitrogen dioxide (NO2) exposure levels, which once more implies that more people are exposed to those high levels.

These results for Portugal and the Lisbon Metropolitan Area are in line with those obtained for spatial disparity in UK (Overman and Xu, 2022). The analysis for UK labor market also shows that the difference is driven by the wages (e.g., labor demand and supply) if the higher-paid are typically concentrated in big cities and capitals.

For each spatial specification considered above (the whole country, four groups of parishes in the country, LMA, four groups of parishes in LMA), I perform the econometric analysis for all patients, for both genders, together and separately. After, I divided all the patients into age cohorts of 5 years each; the cohort 0 – 5 years old is divided into 0 – 1 and 2 – 5 years old, respectively. As the hospital admissions dataset contains data on both the date of birth and the date of hospital admission for the cohort 0 – 1 years old, I calculate age in days, and, therefore, I perform the analysis for the 3-month periods (0 – 3 months, 3 – 6 months, etc.). I consider hospital admissions due to general respiratory-related reasons (ICD 10 code “J”) and specific respiratory-related reasons that are associated with air pollution (pneumonia (ICD 10 codes are

J12 - J18, P23), chronic obstructive pulmonary disease (COPD) (ICD 10 codes are J40 – J44), and acute asthma (ICD 10 codes are J45-J46). Below, the most important results obtained are shown.

4. Results

Table 10 presents the results for all the parishes in Portugal. A 1 microg/m3 increase in the daily concentration of nitrogen dioxide (NO2) increases the number of hospital admissions due to specific respiratory-related reasons (pneumonia, chronic obstructive pulmonary disease (COPD), asthma) by 0.8%, and the impact occurs on the same day of the increase. To derive more "detailed" disaggregated nitrogen dioxide (NO2) impact estimates, I divided each age cohort by gender and performed the econometric analysis for each age-gender group. A 1 microg/m3 increase in the daily concentration of nitrogen dioxide (NO2) leads to a 2.6% increase for the 2 – 5 years cohort.

The hospital admissions dataset contains data on each patient's date of birth and admission to the hospital. This allows me to calculate a patient's age in days and explore the 0 – 1 years old cohort in more detail. Table 10 presents the results of the estimation of the impact of nitrogen dioxide (NO2) daily concentrations on the number of hospital admissions due to specific respiratory-related reasons for children in the range of 0 – 6 months, 6 – 12 months, and more granularly between 0 – 3, 3 – 6, 6 – 9, and 9 – 12 months old[27]. Disaggregating for three months was chosen as children in Portugal can start attending nurseries at 3 months old, which means that their exposure to the outside world increases significantly after that age. A 1 microg/m3 increase in a daily concentration of nitrogen dioxide (NO2) leads to a 7.5% increase in the number of hospital admissions due to specific respiratory-related reasons among children 9 – 12 months old two days after the increase has occurred. The female population drives the effect in both cohorts, 0 – 1 years old and 9 – 12 months old. A 1 microg/m3 increase in a daily concentration of nitrogen dioxide (NO2) leads to a 3.8% increase in the daily number of hospital admissions for the female cohort of 0 – 1 years old and to a 12.1% increase for the female cohort of 9 – 12 months old (Table 10).

As mentioned, Portugal has a high level and variability in nitrogen dioxide (NO2) concentrations. Therefore, I divided all the parishes into four groups, depending on the average

[27] The 0 – 3 months cohort consists of patients who were up to 92 days old by the date of submission, 3 – 6 months – between 93 and 183 days, 6 – 9 months – between 184 and 275 days, and 9 – 12 months – between 276 and 366 days.

concentration of nitrogen dioxide (NO2). On average, parishes in group one have the lowest levels of NO2 exposure, and parishes in group four are exposed to the highest concentrations registered. Table 11 presents the regression results for each of the groups. Only in group four a significant impact of NO2 on hospital admissions is identified for the patients of all ages all over the country. A 1 microg/m3 increase in a daily concentration of nitrogen dioxide (NO2) leads to a 1.1% increase in the number of hospital admissions due to specific respiratory-related reasons on the same day. For the cohort 2 – 5 years old, the impact is significant also only for the parishes in group four. In this case, a 1 microg/m3 increase in the daily concentration of nitrogen dioxide (NO2) leads to a 3.3% increase in the daily number of hospital admissions. The magnitude of the impact increased by 0.7% (27% increase, from 2.6% to 3.3%), with the average daily nitrogen dioxide (NO2) concentration increasing by 0.8 microg/m3 (57% increase from 1.4 to 2.2 microg/m3). The fact that the hospital admissions happen on the same day as the increase in exposure and are only significant for group four parishes can be explained by consistently higher average concentrations that residents of these parishes are exposed to. As they experience elevated levels of NO2 every day and, therefore, their respiratory system is under constant pressure, the negative reaction to marginal increases in pollution is probably more detrimental to their more vulnerable health condition, thus explaining why the magnitude of the impact is higher. Moreover, this suggests a non-linear response to the marginal increases in the NO2 concentration levels.

Table 12 presents the results for one of the areas in group four, Lisbon Metropolitan Area, the most populated area in Portugal. A 1 microg/m3 increase in a daily concentration of nitrogen dioxide (NO2) leads to a 9.3% increase in the number of hospital admissions due to specific respiratory-related reasons on the same day among children 0 – 1 years old and to a 17.7% increase among children 2 – 5 years old. Females drive the effects for the general population and to children's cohorts. The effect in the cohort 0 – 1 years old, which was not identified in the previous analysis, is driven by children between 6 and 12 months old when they have already significantly more interaction with the outside world than at a lower age. This finding may suggest the nonlinear response to persistent NO2 exposure among small children and the existence of some exposure threshold level. If this is the case, this result is of major relevance for policy purposes, as it will constitute a more solid informed basis for regulators to adjust the standard levels.

Table 13 presents the regression results for the four groups of the Lisbon Metropolitan Area. A significant impact is identified for the parishes that belong to group four. A 1 microg/m3 increase in a daily concentration of nitrogen dioxide (NO2) leads to a 20.2%

increase in the number of hospital admissions due to specific respiratory-related reasons on the same day among children 2 – 5 years old.

I find a significant impact of daily concentrations (NO2) on the number of hospital admissions due to specific respiratory-related reasons among the youngest cohorts, 0 - 1 and 2 – 5 years old. From 2016 to 2018, there were 1 466 hospital admissions for females between 0 and 1 years old and 3 659 hospital admissions in the cohort 2 – 5 years old. A 1 microg/m3 increase in a daily concentration of nitrogen dioxide (NO2) leads to 1 522 and 3 755 additional hospital admissions in the three years, respectively, leading to 152 additional hospital admissions. On average, such a hospital admission lasts for five days; therefore, this increase will result in 760 extra days, which increases the pressure on the country's hospital network. The dataset on hospital admissions does not include the costs of individual admissions. However, according to the hospitalization tariffs, the daily price for an asthma episode may vary between 351.55 and 1 087.74 euros (2018)[28]; therefore, the three-year cost of a 1 microg/m3 increase in the daily concentration of nitrogen dioxide (NO2) may result in additional public spending between 267 178 and 826 682 euros (2018). The decrease by one standard deviation (1.7 microg/m3) will result in savings from 454 203 to 1 405 359 euros (2018). In 2018, the healthcare budget of Portugal was 10.2 billion euros[29]. Despite the significantly smaller value of savings compared to the healthcare budget of 2018 (10.2 billion euros), this value represents a lower bound to the cost estimation as it uses the tariffs and describes only costs related to the hospitals and does not take into account the future possible costs in child development, productivity, or future earnings. For instance, parents who cannot go to work to take care of their children may eventually impact more women, which is associated to gender gaps and the consequent generated inequalities in marketplace which are not also reflected in these calculations but cannot be ignored.

5. Conclusions

[28] The exact tariff depends on the severity level of hospital admission. Asthma has four severity levels: 1 is the least severe case, and 4 is the most severe one. One day of treatment of hospital admission due to asthma with a severity level 1 amounts to 351.55 euros, with a severity level 2 is 612.27 euros, a severity level 3 is 652.14 euros, and a severity level 4 is 1 087.74 euros. The values were obtained from the National Table of Homogeneous Diagnostic Groups, defined by Ordinance No. 254/2018, the Regulations and Price Tables of Institutions and Services integrated into the National Health System (September 7, 2018).

[29] State budget 2018. Sic Notícias. (https://sicnoticias.pt/arquivo/oe-2018/2017-10-13-Orcamento-para-a-saude-vai-rondar-os-10.200-milhoes-de-euros)

In this study, I estimate the impact of daily nitrogen dioxide (NO2) concentrations on the number of hospital admissions due to specific respiratory-related reasons at a parish level in Portugal. I find a significant negative impact on the youngest cohorts, 0 – 1 and 2 – 5 years old. Females drive the impact in the cohort 0 – 1 years old. A one standard deviation decrease in the daily nitrogen dioxide concentration may lead to up to 1.4 million euros in savings for the Portuguese national health system. This value represents a lower bound of the possible benefits of reducing air pollution.

The air pollution epidemiological literature supports the results found. It shows that children are more susceptible to air pollution because their lung and immune systems are less developed, they breathe more air per unit of body weight, and they are more active (Strickland et al., 2010). However, the results regarding the impact due to sex differences are inconclusive[30]. Clark et al. (2010) estimate the impact of traffic air pollution exposure on asthma incidences during the first 2 years of life and find that females are more affected. Despite finding fewer incidences, the association with air pollutants is stronger. The mechanisms of how air pollution impacts the respiratory system have yet to be clearly identified. Still, the possible explanations include differences in lung development, immunoglobin serum level that is higher in girls, narrower airways for boys (Dong et al., 2011), higher deposition levels in the lungs for females (Luginaah et al., 2005), and decrease in forced expiratory volume which is more significant for women (Rojas-Martinez et al., 2007). Moreover, women as a group are poorer than men, and they have greater exposure to air pollution on average due to childcare, cooking and, in general the gender gap (Luginaah et al., 2005).

Based on satellite reanalysis data all the parishes in Portugal were divided into four groups, where those in group one have the lowest daily nitrogen dioxide concentrations, while in group four have the highest. The same type of division was undertaken for the Lisbon Metropolitan Area, the country's most populated area. Most parishes that belong to group four in the Lisbon Metropolitan Area do not belong to the city of Lisbon, except for six parishes: Belém, Misericórdia, Penha de França, Santa Maria Maior, Santo António, and São Vicente. Except for Belém and Santo António, these parishes represent the historical downtown of Lisbon. The most expensive houses in Portugal in 2023 are located on Rua Garrett, in the Santa Maria Maior

[30] In epidemiology, the term "sex" describes the biological characteristics of patients, and the term "gender" describes socio-economic characteristics, for example, social behavior and roles (Clougherty, 2010).

parish[31]. The Santo António parish includes the city's business center and one of the most fashionable streets in Portugal, Avenida da Liberdade, where all the most expensive brands can be found and beautiful buildings from the end of the 19th century and early 20th century. Currently, there is no efficient urban policy to combat local air pollution in Portugal. Therefore, based on the results of the performed analysis and considering the geography of the most polluted areas of Lisbon, new Low Emission Zones in the historical center of Lisbon could be an efficient solution to decrease the ambient nitrogen dioxide concentrations[32]. Low Emission zones have been introduced in 14 countries of the European Union, the UK included.[33] The literature shows that this policy may efficiently decrease ambient nitrogen dioxide concentrations (Carslaw and Beevers, 2002), improving health outcomes (Malina and Scheffler, 2015). Hopefully, this type of policy, informed by the results obtained in this study, if adequately implemented, may contribute to decrease congestion in the city's historical center with positive spillovers on the ambient traffic pollutant concentrations, such as of nitrogen dioxide, improving the population´s wellbeing.

[31] Jornal de Negócios. Sílvia Abreu. August 26, 2023. (https://www.jornaldenegocios.pt/empresas/imobiliario/detalhe/lisboa-tem-oito-das-10-ruas-mais-caras-de-portugal#:~:text=A%20informa%C3%A7%C3%A3o%20%C3%A9%20divulgada%20pelo,a%20Rua%20Garrett%2C%20no%20Chiado.)

[32] There is a Low Emission Zone policy in Lisbon: cars made before the year 2000 cannot enter the city's historical center. Still, this policy is not enforced,.

[33] EU: Low Emission Zones (LEZs). (https://dieselnet.com/standards/eu/lez.php)

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Appendix

A1. Tables

Table 1: Summary statistics at a parish level, Census 2021, Portugal

Total number of residents	10 343 066
Average number of residents per parish	8 189
Minimum number of residents per parish	19
Maximum number of residents per parish	68 649
Average monthly income per individual per municipality (euros 2018)	943.1
Average monthly rent (euros 2021)	236.09
Higher education completed (%)	12
Average age (years)	50
Average commuting time (minutes)	18.6
0 – 9 years old (%)	6
10 – 19 years old (%)	8
20 – 29 years old (%)	9
30 – 39 years old (%)	10
40 – 49 years old (%)	13
50 – 59 years old (%)	15
60 – 69 years old (%)	16
70 – 79 years old (%)	13
80 – 89 years old (%)	9
90 – 99 years old (%)	2
100 years old and more (%)	0.04
Male (%)	48
Female (%)	52
Work and live in the same parish (%)	30
Work and live in the same municipality, but different parishes (%)	40
Work in another municipality than live (%)	29

Table 2: Summary statistics of pollutant concentrations that are measured by the Portuguese monitoring network,
January 1, 2016, - December 31, 2018, Portugal

Pollutant	# of observations	Mean value	Standard deviation	Minimum value	Maximum value	# of missing observations
			Hourly			
Carbon monoxide (CO)	359 751	0.3	0.2	0	5.8	1 393 833
Nitrogen dioxide (NO2)	1 194 640	30.7	99.4	0	3 614.0	558 944
Nitric oxide (NO)	1 165 154	9.3	26.4	0	896.3	588 430
Nitrogen oxides (Nox)	1 187 406	58.4	256.3	0	9 988.0	566 178
Ozone (O3)	997 172	60.5	52.8	0	1 927.0	756 412
Particulate matter (PM10)	1 283 977	23.6	45.6	0	1 664.0	469 607
Particulate matter (PM2.5)	432 927	7.7	7.8	0	290.0	1 320 657
Sulfur dioxide (SO2)	561 483	2.5	6.2	0	532.0	1 192 101
Benzol (C6H6)	74 859	0.4	0.8	0	15.9	1 678 725

Hourly observations: The hourly data are obtained from 67 active stations between January 1, 2016, and December 31, 2018. All pollutants are measured in $\mu g/m^3$. Each station except the station PM03104 has 26 304 observations (24 hours * 1096 days). Total number of observations: 1 753 584.

Table 3: Summary statistics of pollutant concentrations derived from the reanalysis tools, January 1, 2016, - December 31, 2018, Portugal

Pollutant	# of observations	Mean value	Standard deviation	Minimum value	Maximum value	# of missing observations
	NASA Aura Validation Data Centre (AVDC), daily					
Nitrogen dioxide (NO2)	1 079	1.4	1.7	0.2	35.1	0
	CAMS reanalysis tool, daily					
Pollutant	# of observations	Mean value	Standard deviation	Minimum value	Maximum value	# of missing observations
Carbon monoxide (CO)	1 096	138.1	11.9	109.3	207.2	0
Nitrogen dioxide (NO2)	1 096	4.2	0.5	2.5	7.5	0
Ozone (O3)	1 096	59.9	6.9	36.2	67.1	0
Particulate matter (PM10)	1 096	15.8	1.4	12.3	24.3	0
Particulate matter (PM2.5)	1 096	10.1	1.2	7.1	17.9	0
Sulfur dioxide (SO2)	1 096	2.7	0.3	1.4	3.2	0

AVDC reanalysis tool: The daily concentrations were obtained with the AVDC reanalysis dataset. The period of observations is between January 1, 2016, and December 31, 2018. The total number of observations is less than 1 096 days as the satellite was not registering pollutant concentration on some days. The pollutant's concentration is measured in $\mu g/m^3$. CAMS reanalysis tool: The daily concentrations were obtained from the CAMS reanalysis tool. There are 91 unique points, each with 1 096 registries for every pollutant. All the pollutants are measured in $\mu g/m^3$.

Table 4: Summary statistics of daily pollutant concentrations at a parish level, satellite reanalysis tools data, January 1, 2016, - December 31, 2018, Portugal

Pollutant	# of observations	Mean value	Standard deviation	Minimum value	Maximum value
Nitrogen dioxide (NO_2)	3 091 335	1.4	2.9	0.1	213.3
Ozone (O_3)	3 091 335	52.3	8.4	10.2	76.3
Particulate matter (PM_{10})	3 091 335	17.1	6.5	5.7	53.8
Particulate matter ($PM_{2.5}$)	3 091 335	11.4	4.9	3.7	38.8

All pollutants are measured in $\mu g/m^3$. Total number of observations: 3 091 335.

Table 5: Summary statistics of the hospital admission data,
January 1, 2016, - December 31, 2018, Portugal

	# of observations	Mean value	Standard Deviation	Minimum value	Maximum value
All types of hospital admissions					
Age	4 438 473	57.00	24.15	0	110
Days in the hospital	4 438 473	3.90	10.29	0	3 885
Birth weight	194 953	3 158	548.64	100	8 740
National Health System	4 438 473	0.96	0.19	0	1
Outpatient hospital admissions					
	# of observations	Mean value	Standard Deviation	Minimum value	Maximum value
Age	2 191 720	61.04	18.28	0	106
Days in the hospital	2 191 720	0	0	0	0
Birth weight	589	2 633	977	280	5 140
National Health System	2 191 720	0.97	0.18	0	1
Inpatient hospital admissions					
	# of observations	Mean value	Standard Deviation	Minimum value	Maximum value
Age	2 246 753	53.06	28.19	0	110
Days in the hospital	2 246 753	7.70	13.41	0	3 885
Birth weight	194 620	3 159	547	100	8 740
National Health System	2 246 753	0.96	0.20	0	1

Table 6: Summary statistics of the hospital admission due to respiratory-related reasons data,
January 1, 2016, - December 31, 2018, Portugal

	# of observations	Mean value	Standard Deviation	Minimum value	Maximum value
All types of hospital admissions					
Age	279 446	58.86	29.70	0	109
Days in the hospital	279 446	7.38	13.06	0	3 885
National Health System	279 447	0.96	0.19	0	1
Outpatient hospital admissions					
Age	39 062	42.63	27.14	0	105
Days in the hospital	39 062	0	0	0	0
National Health System	39 062	0.99	0.09	0	1
Inpatient hospital admissions					
Age	240 384	61.50	29.26	0	109
Days in the hospital	240 384	8.58	13.71	0	3 885
National Health System	240 384	0.96	0.20	0	1

Table 7: Summary statistics for four groups of parishes, Portugal, January 1, 2016 – December 31, 2018

	Group one	Group two	Group three	Group four
Total number of residents	845 644	1 450 360	1 686 301	5 783 812
Average number of residents per parish	1 179	2 026	2 355	8 078
Average monthly income per individual per municipality (euros 2018)	747.4	763.0	788.2	848.2
NO2 (µg/m^3)	0.8	1.0	1.4	2.2
PM10 (µg/m^3)	14.5	17.5	18.2	17.9
PM25 (µg/m^3)	9.8	11.8	12.2	11.9
O3 (µg/m^3)	51.4	51.2	51.9	54.8
Average monthly rent (euros 2021)	228.81	240.16	243.33	232.33
Higher education completed (%)	9.5	10.4	11.7	16.3
Average age (years)	55	52	49	45
Average commuting time (minutes)	17.9	18.2	19.6	19.6
0 – 9 years old (%)	5	6	7	8
10 – 19 years old (%)	7	8	9	10
20 – 29 years old (%)	7	8	9	11
30 – 39 years old (%)	8	8	10	12
40 – 49 years old (%)	11	12	14	15
50 – 59 years old (%)	14	15	15	15
60 – 69 years old (%)	17	17	15	13
70 – 79 years old (%)	16	15	13	10
80 – 89 years old (%)	12	10	8	5
90 – 99 years old (%)	3	2	2	1
100 years old and more (%)	0.1	0.1	0.03	0.02
Male (%)	48	48	48	48
Female (%)	52	52	52	52
Work and live in the same parish (%)	38	33	25	25
Work and live in the same municipality, but different parishes (%)	37	38	42	41
Work in another municipality than live (%)	24	28	32	34

Table 8: Summary statistics at a parish level, Census 2021, Lisbon Metropolitan Area

Total number of residents	2 870 208
Average number of residents per parish	24 324
Minimum number of residents per parish	1 566
Maximum number of residents per parish	68 649
Average monthly income per individual per municipality (euros 2018)	1 168.2
Average monthly rent (euros 2021)	222.40
Higher education completed (%)	27.0
Average age (years)	44
Average commuting time (minutes)	24.8
0 – 9 years old (%)	9
10 – 19 years old (%)	10
20 – 29 years old (%)	11
30 – 39 years old (%)	13
40 – 49 years old (%)	16
50 – 59 years old (%)	12
60 – 69 years old (%)	13
70 – 79 years old (%)	10
80 – 89 years old (%)	5
90 – 99 years old (%)	1
100 years old and more (%)	0.02
Male (%)	48
Female (%)	52
Work and live in the same parish (%)	29
Work and live in the same municipality, but different parishes (%)	30
Work in another municipality than live (%)	41

Table 9: Summary statistics for each of quantiles, Lisbon Metropolitan Area, January 1, 2016 – December 31, 2018

	Group one	Group two	Group three	Group four
Total number of residents	458 979	674 861	752 382	983 986
Average number of residents per parish	15 299	22 495	25 944	33 931
Average monthly income per individual per municipality (euros 2018)	1 079.4	895.6	952.7	1 177.1
NO2 (μg/m^3)	1.6	2.0	2.3	2.4
PM10 (μg/m^3)	15.7	16.0	16.0	16.0
PM25 (μg/m^3)	10.1	10.2	10.2	10.2
O3 (μg/m^3)	63.2	64.4	64.4	64.4
Average monthly rent (euros 2021)	199.28	239.65	219.83	230.84
Higher education completed (%)	21.3	21.9	34.0	31.4
Average age (years)	44	44	44	44
Average commuting time (minutes)	24.2	26.9	23.6	24.5
0 – 9 years old (%)	9	9	9	9
10 – 19 years old (%)	11	11	10	10
20 – 29 years old (%)	10	10	12	12
30 – 39 years old (%)	12	12	13	13
40 – 49 years old (%)	17	16	15	15
50 – 59 years old (%)	14	12	13	13
60 – 69 years old (%)	12	13	11	11
70 – 79 years old (%)	10	10	10	10
80 – 89 years old (%)	5	5	6	5
90 – 99 years old (%)	1	1	1	1
100 years old and more (%)	0.002	0.002	0.004	0.003
Male (%)	48	48	47	47
Female (%)	52	52	53	53
Work and live in the same parish (%)	33	30	25	27
Work and live in the same municipality, but different parishes (%)	24	21	45	31
Work in another municipality than live (%)	42	49	30	42

Table 10: Impact of nitrogen dioxide (NO2) daily concentrations on the number of hospital admissions due to specific respiratory-related reasons, January 1, 2016 – December 31, 2018, Portugal

Both genders						
Nitrogen dioxide (NO2)						
	All age groups	0 – 1 years old	2 – 5 years old	6 – 18 years old	6 – 12 months	9 – 12 months
On the day of the hospital admission	0.008*** (0.003)	0.012 (0.015)	0.026* (0.014)	-0.007 (0.020)	0.046 (0.031)	0.072* (0.039)
One day before the hospital admission	0.002 (0.003)	0.002 (0.018)	-0.012 (0.020)	-0.018 (0.024)	-0.019 (0.036)	-0.036 (0.045)
Two days before the hospital admission	-0.002 (0.003)	0.002 (0.015)	-0.010 (0.018)	0.026 (0.017)	-0.012 (0.029)	-0.021 (0.033)
Female						
Nitrogen dioxide (NO2)						
	All age groups	0 – 1 years old	2 – 5 years old	6 – 18 years old	6 – 12 months	9 – 12 months
On the day of the hospital admission	0.006 (0.004)	0.037** (0.017)	0.007 (0.027)	-0.030 (0.019)	0.094** (0.037)	0.114** (0.051)
One day before the hospital admission	0.007 (0.005)	-0.006 (0.023)	-0.016 (0.034)	0.006 (0.027)	-0.082* (0.045)	-0.107 (0.066)
Two days before the hospital admission	-0.004 (0.004)	-0.019 (0.020)	0.011 (0.027)	0.024 (0.024)	0.004 (0.033)	0.002 (0.049)

The dependent variable is the number of hospital admissions due to specific respiratory-related reasons (pneumonia, chronic obstructive pulmonary disease (COPD), asthma). Nitrogen dioxide (NO2) is measured in $\mu g/m^3$. Estimates from the negative binomial model, equation (1) in the main text. All regressions control for parish fixed effects. Standard errors are reported in parentheses. The negative coefficient in 6 – 12 months cohort most probably comes from the fact that if the parents decided to stay at home and not go to the hospital on day one, children often get better on the next day and the possible hospital admissions have not occurred. * p<0.1; ** p<0.05; *** p<0.01

Table 11: Impact of nitrogen dioxide (NO_2) daily concentrations on the number of hospital admissions due to specific respiratory-related reasons, January 1, 2016 – December 31, 2018, Portugal

	Group one	Group two	Group three	Group four
All age groups, both genders				
On the day of the hospital admission	0.019	0.006	0.004	0.011***
	(0.018)	(0.007)	(0.006)	(0.004)
One day before the hospital admission	-0.010	0.001	-0.006	-0.001
	(0.021)	(0.009)	(0.008)	(0.005)
Two days before the hospital admission	-0.005	0.003	0.008	-0.001
	(0.018)	(0.007)	(0.006)	(0.004)
2 – 5 years old, both genders				
On the day of the hospital admission	0.027	-0.010	-0.020	0.032**
	(0.076)	(0.037)	(0.048)	(0.013)
One day before the hospital admission	-0.063	0.013	0.034	-0.034
	(0.100)	(0.045)	(0.044)	(0.026)
Two days before the hospital admission	0.040	0.013	-0.019	0.006
	(0.052)	(0.033)	(0.036)	(0.023)

The dependent variable is the number of hospital admissions due to specific respiratory-related reasons (pneumonia, chronic obstructive pulmonary disease (COPD), asthma). Nitrogen dioxide (NO_2) is measured in $\mu g/m^3$. Estimates from the negative binomial model, equation (1) in the main text. All regressions control for parish fixed effects. Standard errors are reported in parentheses. * p<0.1; ** p<0.05; *** p<0.01

Table 12: Impact of nitrogen dioxide (NO2) daily concentrations on the number of hospital admissions due to specific respiratory-related reasons, January 1, 2016 – December 31, 2018, Lisbon Metropolitan Area

	All age groups	0 – 1 years old	2 – 5 years old	6 – 18 years old	6 – 12 months
Both genders					
On the day of the hospital admission	0.033*** (0.011)	0.089* (0.052)	0.163*** (0.059)	0.015 (0.078)	0.124 (0.106)
One day before the hospital admission	0.009 (0.013)	-0.001 (0.069)	-0.079 (0.075)	-0.130 (0.091)	-0.026 (0.146)
Two days before the hospital admission	0.005 (0.011)	0.007 (0.060)	-0.055 (0.064)	0.082 (0.067)	-0.046 (0.129)
Female					
On the day of the hospital admission	0.050*** (0.016)	0.198*** (0.069)	0.183** (0.090)	0.017 (0.115)	0.231* (0.136)
One day before the hospital admission	0.010 (0.019)	-0.080 (0.100)	-0.074 (0.115)	-0.247* (0.137)	-0.283 (0.234)
Two days before the hospital admission	-0.013 (0.016)	-0.007 (0.087)	-0.075 (0.096)	0.188** (0.092)	0.084 (0.207)

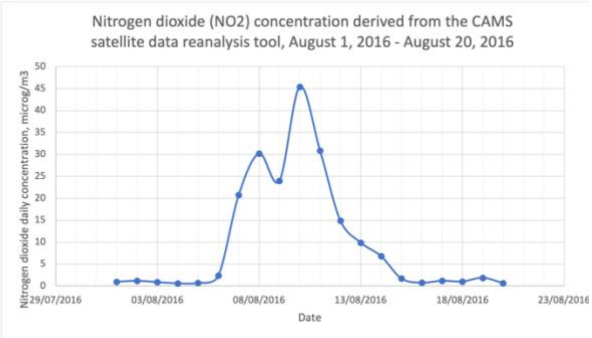
The dependent variable is the number of hospital admissions due to specific respiratory-related reasons (pneumonia, chronic obstructive pulmonary disease (COPD), asthma). Nitrogen dioxide (NO2) is measured in $\mu g/m^3$. Estimates from the negative binomial model, equation (1) in the main text. All regressions control for parish fixed effects. Standard errors are reported in parentheses. The negative coefficient in the 6 – 18 years old cohort most probably comes from the fact that if a teenager did not go to the hospital on day one, she would prefer to continue staying home during the next day, so the possible hospital admissions would not happen. If she still feels unwell for the second day in a row, she will probably go to the hospital. Therefore, the impact is significant to days after the concentration's increase. * p<0.1; ** p<0.05; *** p<0.01

Table 13: Impact of nitrogen dioxide (NO2) daily concentrations on the number of hospital admissions due to specific respiratory-related reasons,
January 1, 2016 – December 31, 2018, Lisbon Metropolitan Area

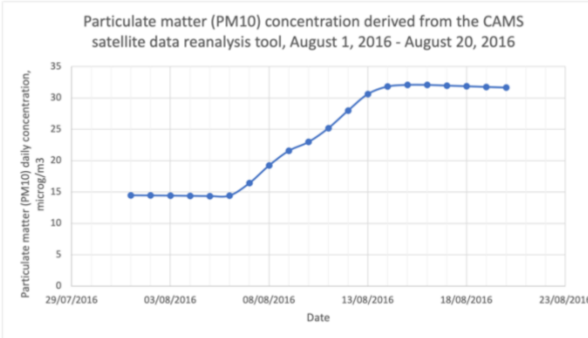
2 – 5 years old, both genders				
	Group one	Group two	Group three	Group four
On the day of the	0.137	-0.294	-0.145	0.184**
hospital admission	(0.203)	(0.282)	(0.169)	(0.078)
One day before the	0.015	0.088	0.005	-0.052
hospital admission	(0.232)	(0.323)	(0.240)	(0.096)
Two days before the	-0.127	0.062	0.141	-0.057
hospital admission	(0.236)	(0.193)	(0.188)	(0.079)

The dependent variable is the number of hospital admissions due to specific respiratory-related reasons (pneumonia, chronic obstructive pulmonary disease (COPD), asthma). Nitrogen dioxide (NO2) is measured in $\mu g/m^3$. Estimates from the negative binomial model, equation (1) in the main text. All regressions control for parish fixed effects. Standard errors are reported in parentheses. * p<0.1; ** p<0.05; *** p<0.01

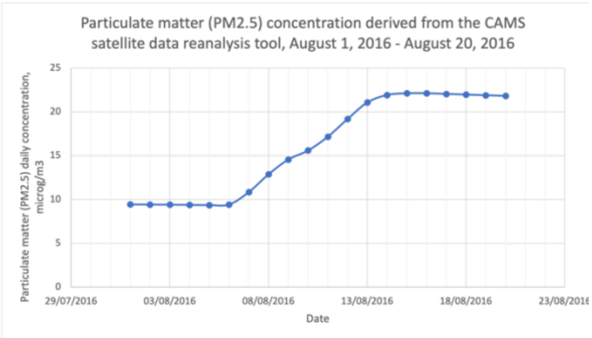
A2. Figures



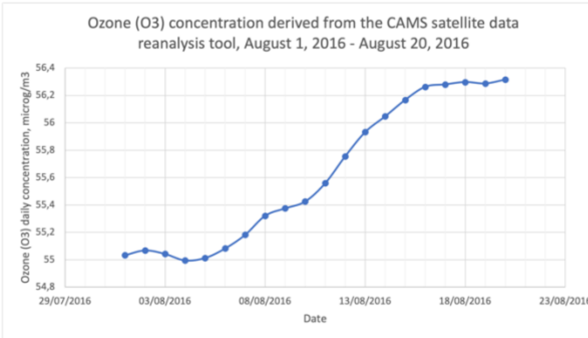
Daily nitrogen dioxide (NO2) concentrations



Daily particulate matter (PM10) concentrations



Daily particulate matter (PM2.5) concentrations.



Daily ozone (O3) concentrations.

Figure 1: Daily pollutant concentrations in the northern part of continental Portugal, the Porto Metropolitan Area between August 1, 2016, and August 20, 2016.

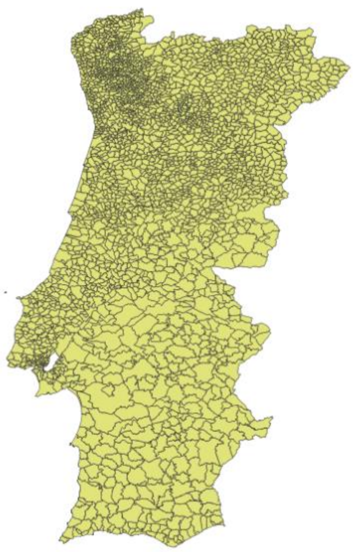


Figure 2: Map of parishes in continental Portugal.

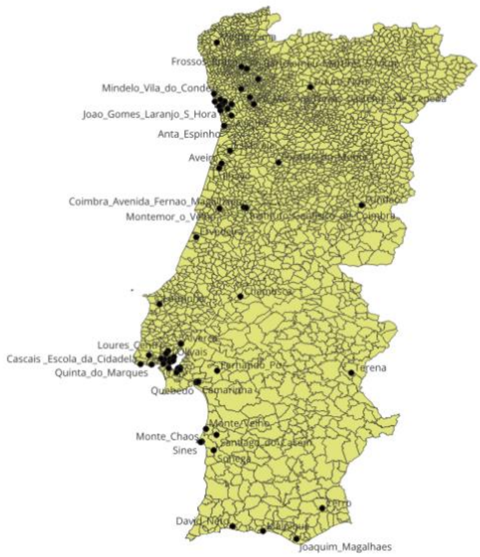


Figure 3: Map of monitoring stations in continental Portugal.

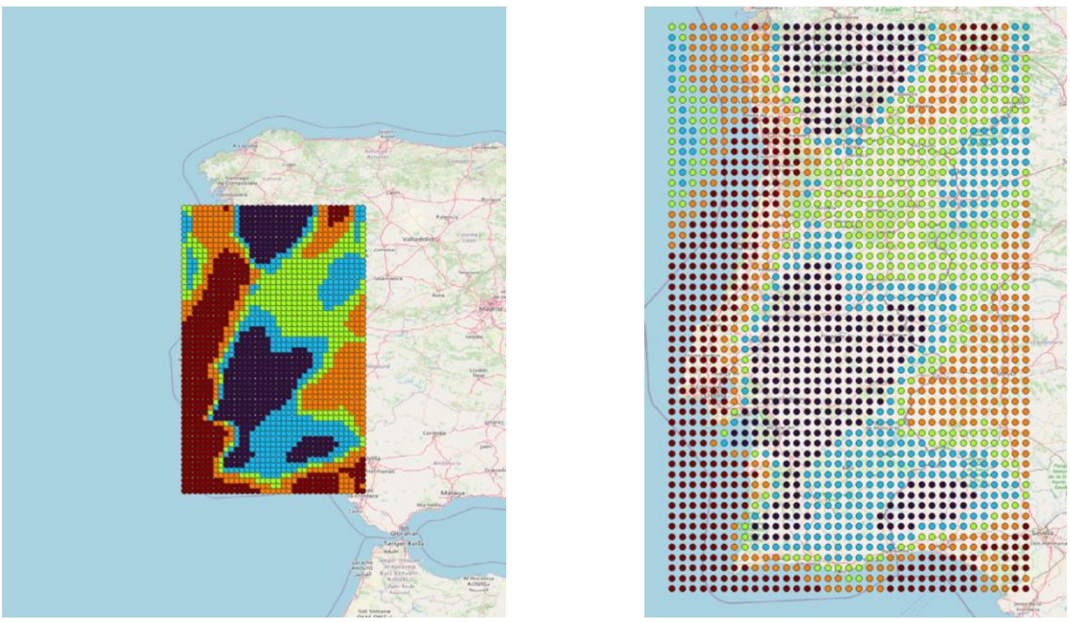


Figure 4: Left: Portugal covered by the AVDC map of points (0.1 by 0.1 degrees, ~ 11 by 11 km). Colors represent five bins of nitrogen dioxide (NO2) concentrations measured on February 3, 2016. The dark blue refers to the lowest concentration bin, the dark red refers to the highest concentration bin. Right: Zoom-in into the AVDC map of points.

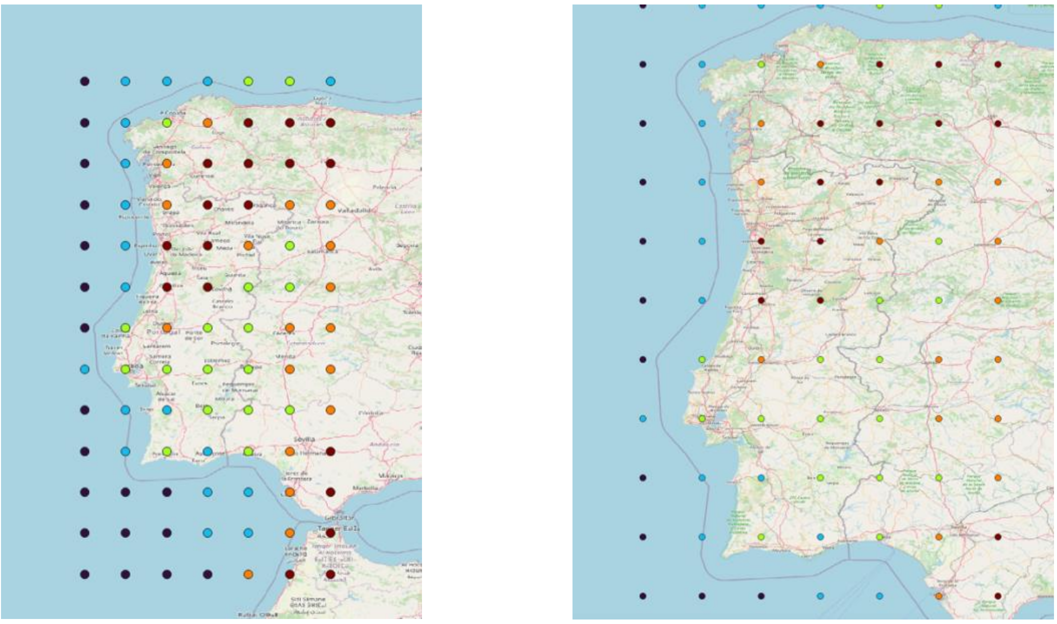
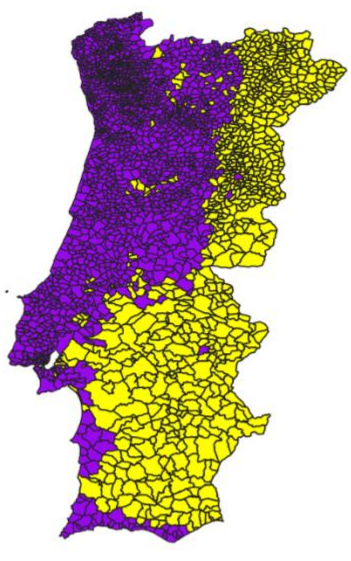
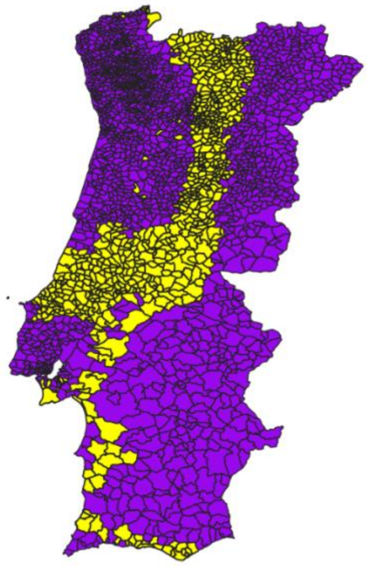


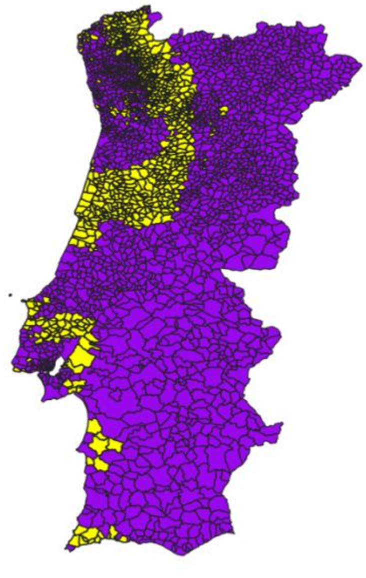
Figure 5: Left: Portugal covered by the CAMS map of points (0.75 by 0.75 degrees, ~ 80 by 80 km). Colors represent five bins of nitrogen dioxide (NO2) concentrations measured on February 3, 2016. The dark blue refers to the lowest concentration bin, the dark red refers to the highest concentration bin. Right: Zoom-in into the CAMS map of points.



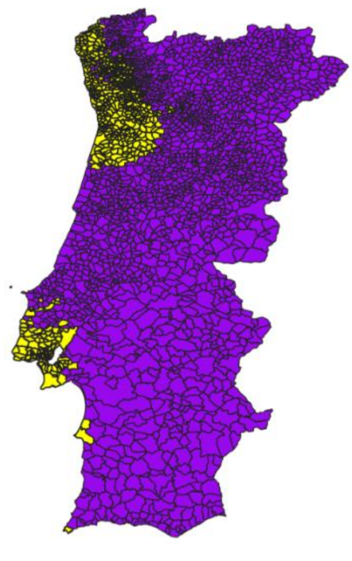
Group one. The average NO2 daily concentration is 0.8 µg/m^3



Group two. The average NO2 daily concentration is 1.0 µg/m^3

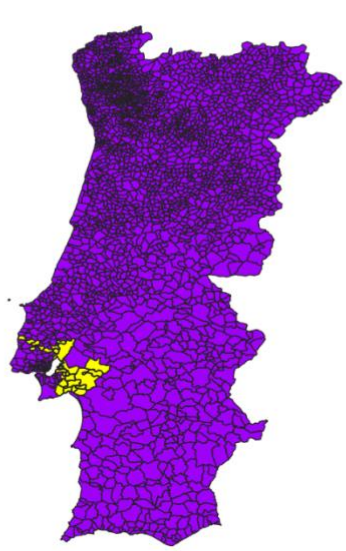


Group three. The average NO2 daily concentration is 1.4 µg/m^3

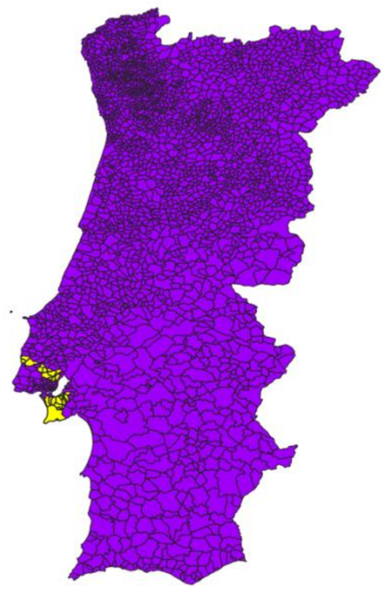


Group four. The average NO2 daily concentration is 2.2 µg/m^3

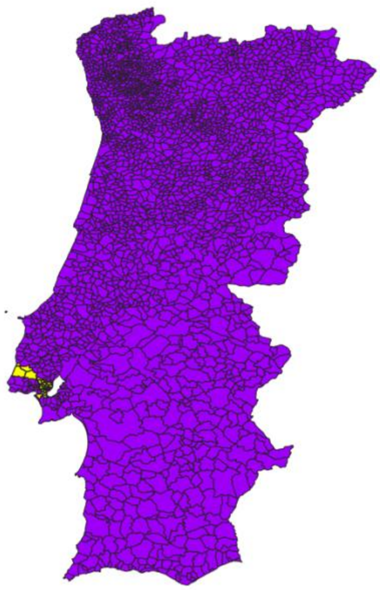
Figure 6: Four groups of parishes formed based on the average daily nitrogen dioxide (NO2) concentration. Group one contains the parishes with the lowest daily concentrations, group four contains the parishes with the highest levels.



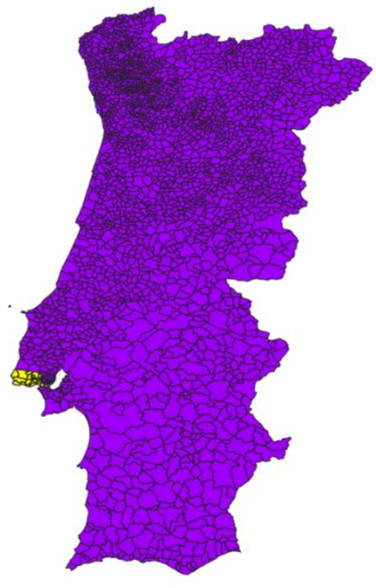
Group one. The average NO2 daily concentration is 1.6 μg/m^3



Group two. The average NO2 daily concentration is 2.0 μg/m^3



Group three. The average NO2 daily concentration is 2.3 μg/m^3



Group four. The average NO2 daily concentration is 2.4 μg/m^3

Figure 7: Four groups of parishes formed based on the average daily nitrogen dioxide (NO2) concentration in Lisbon Metropolitan Area (LMA). Group one contains the parishes with the lowest daily concentrations, group four contains the parishes with the highest levels.